

On a possible manifestation of f_1 trajectory in J/ψ photoproduction

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Abstract

We analyze a possible manifestation of f_1 -trajectory in elastic J/ψ photoproduction at high energy and large momentum transfer. In spite of the small contribution of f_1 -trajectory in total cross sections, it becomes significant in various spin observables. In particular, we show that the crucial test for f_1 -exchange can be made by measuring the single beam- and double parity- and beam-target asymmetries at large momentum transfers, where a strong deviation from the exchange of conventional Pomerons is expected. This effect is caused by the interference of natural (Pomeron) and unnatural (f_1) parity exchange parts of amplitude in the region where their contributions become comparable to each other and might be interesting to observe in forthcoming experiments, if feasible.

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Hadronic diffraction has regained popularity in the recent years due to many new interesting experiments at HERA and TEVATRON. One of them is the vector meson photoproduction at HERA. This channel is exciting because here one can study any of the known vector mesons from the lightest ρ to heavier J/ψ and Υ and hope to see the transition from the “soft” to the “hard” regime. The most popular models for description of the diffractive processes at high energy are based on the Regge theory [1] where the corresponding multiparticle exchanges with definite quantum numbers are expressed by the effective exchange of one Regge pole whose propagator is given by $(s/s_0)^{\alpha(t)}$. The Regge trajectory $\alpha(t)$ has a simple linear form $\alpha(t) = \alpha(0) + \alpha' t$ and the main contribution to the elastic forward photoproduction of light vector mesons comes from the Pomeron (so-called “soft” Pomeron) trajectory with intercept 1.08 and slope of 0.25 GeV^{-2} [2]. This leads to rather weak energy dependence of the cross section gradually becoming almost constant at very high energies. However, the Pomeron, though amply used to successfully analyze the high energy total hadron cross sections, still remains mysterious in its partonic content, hence its manifestation in QCD also remains unknown.

Recent studies of elastic vector meson photoproduction data shows that the J/ψ cross-section shows a steep rise with the energy W [3]. This behavior is quite different from that of other light vector mesons like ρ , ω and ϕ which are characterized by a weak dependence of their cross section on energy [$\sigma \propto W^{0.22}$], while for J/ψ it is parameterized as $W^{0.8}$. This new phenomenon drew a lot of attention in this field leading to several models being proposed to explain the data [4–7]. However, this subject still remains controversial. Donnachie and Landshoff [4] claimed that perturbative QCD does not work in this energy region and suggested the use of a small admixture of the second “hard” Reggeon exchange whose trajectory is given by $\alpha_h(t) = 1.418 + 0.1 t$. The conventional mesonic trajectories arising from the fits of Donnachie and Landshoff (for instance, f_2 -trajectory [2,8]) contribute to light vector meson productions at relatively low energies. Most of them have a slope of 0.9 GeV^{-2} and an intercept $\alpha(0) \simeq 0.5$. These trajectories with positive and negative signature are important in the near-threshold region though their contribution decreases with energy. But for description of the J/ψ photoproduction for all energy regions, one must take into account all of the above trajectories: Pomeron, hard Reggeon and mesonic (supersoft) trajectories [10].

The Pomeron and “hard” Reggeon which are dominant at high energy on the phenomenological level are described by the effective “ $C = +1$ photon” exchange which leads to similar spin observables for all components typical for the amplitude with t -channel natural parity exchange. However, so far the study of the unnatural parity exchange trajectories at high energy has not been done widely. Recently, an interesting analysis for testing the new f_1 -trajectory associated with the axial vector meson exchange was done by Kochelev et al. [11], in which the slope of the trajectory was taken to be almost zero. It is very interesting to test the effect of this trajectory even for heavy vector meson J/ψ photoproduction. Since its slope is close to zero, it may be active in the high energy and large momentum transfer region.

In this work, we are concerned with the large momentum transfer region, where the conventional soft Pomeron, the hard Reggeon and f_1 trajectory contribute. We show that the spin observables are sensitive to f_1 -trajectory and will help to differentiate the different components of the amplitude in this region. Let us start with the definition of the kinematical

variables for the $\gamma p \rightarrow J/\psi p$ reaction using standard notation. The four momenta of the incoming photon, outgoing J/ψ , initial (target) and final (recoil) proton are represented by k, q, p and p' , respectively. Hereafter, θ denotes the J/ψ production angle in c.m.s. and $s \equiv W^2 = (p + k)^2$, M_N is the nucleon mass, M_V is the J/ψ mass and m_{f_1} is the f_1 -meson mass. We use the convention of Bjorken and Drell to define the γ matrices and Dirac spinors.

For simplicity we call the “soft” Pomeron and the “hard” Reggeon trajectories [Donnachie-Landshoff(DL)] as the Pomeron part [2,4]. The corresponding invariant amplitude in the standard notation reads,

$$T_{fi}^P = i \sum_{i=s,h} \bar{u}_{m_f}(p') M_{R_i} \epsilon_{V\mu}^*(\lambda_f) ((\gamma \cdot k) g^{\mu\nu} - \gamma^\nu k^\mu) \epsilon_{\gamma\nu}(\lambda_i) u_{m_i}(p), \quad (1)$$

The factor M_{R_i} is given by the conventional Regge pole amplitude,

$$M_{R_i} = 12 a_i s_0 \beta_0^2 \left(\frac{3\Gamma_{V \rightarrow e^+e^-}}{\alpha_{\text{em}} M_V} \right)^{1/2} F_N(t) F_V(t) e^{-i\frac{\pi}{2}(\alpha_i(t)-1)} \left(\frac{s}{s_0} \right)^{\alpha_i(t)}, \quad (2)$$

where $i = s, h$ for soft Pomeron and hard Reggeon, respectively. $V \equiv J/\psi$; $s_0 = 4 \text{ GeV}^2$, $\beta_0 = 1.64 \text{ GeV}^{-1}$; $a_s = 1$, $a_h = 0.05$; $\alpha_{\text{em}} = 1/137$, $\Gamma_{J/\psi \rightarrow e^+e^-} = 5.26 \text{ KeV}$ [12]. The trajectories of these Pomerons are given by,

$$\begin{aligned} \alpha_s(t) &= 1.08 + 0.25 t, \\ \alpha_h(t) &= 1.418 + 0.1 t. \end{aligned} \quad (3)$$

F_N is the isoscalar electromagnetic form factor of the nucleon and F_V is the form factor for the vector-meson-photon-Pomeron coupling [13,14]

$$F_N(t) = \frac{(4M_N^2 - 2.8t)}{(4M_N^2 - t)(1 - t/0.7)^2}, \quad (4)$$

$$F_V(t) = \frac{M_V^2}{(M_V^2 - t)^2} \frac{\mu^2}{2\mu^2 + M_V^2 - t}, \quad (5)$$

with $\mu = 1.1 \text{ GeV}^2$.

For the f_1 -trajectory, we follow the consideration of Ref. [11] where it is assumed that the intercept of this trajectory is equal to 1, in agreement with the low x behavior of the spin-dependent deep inelastic structure function $g_1(x, Q^2) \sim 1/x^\alpha$ with $\alpha = 0.9 \pm 0.2$. Moreover it is assumed that the slope of the trajectory is close to zero, which is in agreement with large t behavior of elastic pp scattering. This means that the excited meson states of this trajectory have very large masses and the total amplitude with unnatural parity is saturated by the lowest $f_1(1285)$ meson exchange which may be expressed in terms of the one boson exchange amplitude. The effective vertices of the axial-vector f_1 -meson interaction with the nucleon and the f_1 -photon-vector-meson interaction reads,

$$V_{f_1 NN} = i g_{f_1 NN} \bar{u}_f \gamma_\mu \gamma^5 \bar{u}_i \xi^\mu, \quad (6)$$

$$V_{f_1 V \gamma} = g_{f_1 V \gamma} \epsilon_{\mu\nu\alpha\beta} \xi^\beta \epsilon_1^\nu \epsilon_2^\alpha M_V^2 k^\mu, \quad (7)$$

where ξ and ϵ are the polarization vectors of the axial vector and vector mesons, respectively, and $g_{f_1 NN} = 2.5$ is fixed from the proton spin analysis. The coupling constant $g_{f_1 V\gamma}$ is extracted from the radiative decay $J/\psi \rightarrow f_1 \gamma$,

$$\Gamma_{V \rightarrow f_1 \gamma} = g_{f_1 V\gamma}^2 \frac{(M_V^2 - M_{f_1}^2)^3 (M_V^2 + M_{f_1}^2)}{96\pi M_V M_{f_1}^2}. \quad (8)$$

Taking $\Gamma_{J/\psi \rightarrow f_1 \gamma} = 56.5$ eV [12], one gets $|g_{f_1 J/\psi \gamma}| = 1.245 \times 10^{-4} \text{ GeV}^{-2}$.

Using the above vertex functions and coupling constants, the corresponding matrix element of the vector meson production can be written as,

$$\begin{aligned} T_{fi} = & ig_{f_1 V\gamma} g_{f_1 NN} F_{f_1 NN}(t) F_{f_1 V\gamma}(t) \frac{m_V^2}{t - m_{f_1}^2} \epsilon_{\mu\nu\alpha\beta} q^\mu \epsilon_V^{*\nu}(\lambda_V) \epsilon_\gamma^\alpha(\lambda_\gamma) \\ & \times \left(g^{\beta\delta} - \frac{(p - p')^\beta (p - p')^\delta}{m_{f_1}^2} \right) \bar{u}_{m_f}(p') \gamma_\delta \gamma_5 u_{m_i}(p), \end{aligned} \quad (9)$$

where $m_{f_1} = 1.285$ GeV. For the $f_1 NN$ vertex, we use the flavor singlet axial vector form factor which is fixed from fitting to elastic pp scattering at high \sqrt{s} and large $|t|$ [11]. (See also [15].)

$$F_{f_1 NN}(t) = 1/(1 - t/m_{f_1}^2)^2. \quad (10)$$

The form factor of the $f_1 V\gamma$ vertex is taken as

$$F_{f_1 V\gamma}(t) = \frac{\Lambda_V^2 - m_{f_1}^2}{\Lambda_V^2 - t} \quad (11)$$

where Λ_V for J/ψ is estimated to be $\Lambda_{J/\psi} = 4.2$ GeV by extrapolating the Λ_V found for ρ and ϕ mesons to the one for the heavy J/ψ meson assuming a linear dependence.

Note that the t -dependence of Eq.(9) is flatter than that of Eq.(1). One reason for this is that the conventional Pomerons have finite trajectory slopes ($\alpha_i > 0$) whereas the slope of f_1 trajectory is almost zero. A slight difference in t -dependence of the corresponding form factors $F_N F_V$ and $F_{f_1 NN} F_{f_1 V\gamma}$ also play a part in determining the overall t -dependence.

Fig. 1 shows the differential cross sections of J/ψ photoproduction for $W = 20$ and 94 GeV. One can see that although the f_1 -contribution is not conspicuously seen at forward production angles (and in total cross sections), it becomes comparable with (and dominant over) the conventional Pomerons in the differential cross sections at large $|t|$. Since its contribution does not qualitatively change the shape of the cross section, it is difficult to extract the f_1 -exchange from the cross section alone. Therefore, we should study the polarization observables for its possible manifestation.

Our analysis of single spin observables shows that the one which is most sensitive to the f_1 -trajectory is the beam asymmetry [16]

$$\Sigma_x \equiv \frac{\text{Tr}[T \sigma_\gamma^x T^\dagger]}{\text{Tr}[T T^\dagger]} = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}, \quad (12)$$

where $\parallel (\perp)$ corresponds to a photon linearly polarized beam along (perpendicular) to the J/ψ production plane. The prediction for Σ_x is shown in Fig.2. All the calculations shown below are done for $W = 94$ GeV. The results shown are for both with (solid curve) and without (dot-dashed curve) f_1 contribution. The pure Pomeron part results in monotonic decreasing of Σ_x from 0 to some negative value depending on t . Solving Eq.(12) using Eq.(9), for pure f_1 channel at high energy and small vector meson production angle θ , we get,

$$\Sigma_x^{f_1} = \frac{s \sin^2 \frac{\theta}{2}}{s \sin^2 \frac{\theta}{2} + M_V^2} > 0, \quad (13)$$

which results in strong increase of Σ_x up to the large positive values exhibiting non-monotonic t -dependence. To further facilitate the experimental test of our predictions, we have also investigated two other spin observables. The first observable is the parity asymmetry defined as [17]

$$P_\sigma \equiv \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U} = 2\rho_{1-1}^1 - \rho_{00}^1, \quad (14)$$

where σ^N and σ^U are the cross sections due to the natural and unnatural parity exchanges and $\rho_{\lambda\lambda'}^i$ are the vector meson spin density matrices. In the region where the natural parity exchange Pomeron part is dominant, one expects $P_\sigma = 1$. Thus, any deviation from this value will be due to the unnatural parity f_1 -exchange. Fig. 3 shows the corresponding prediction. One can see strong t dependence of P_σ which varies from 1 to -1 in a relatively small interval of t .

The second one is the double beam-target asymmetry which is defined as [16],

$$C_{BT} \equiv -A_{LL} = \frac{d\sigma(\Leftarrow) - d\sigma(\Rightarrow)}{d\sigma(\Leftarrow) + d\sigma(\Rightarrow)}, \quad (15)$$

where the arrows denote the relative orientations of the proton and photon helicity, respectively. For both pure natural and unnatural parity exchange amplitudes, C_{BT} is exactly zero. The deviation from this value is due to the interference between natural (Pomeron) and unnatural (f_1 -exchange) parts of the total amplitude. The corresponding calculation is shown in Fig. 4. It can be seen clearly that at some region of t , the beam-target asymmetry deviates from zero considerably. This deviation is proportional to $\text{Re}(T_P T_{f_1})$ and can be used to disentangle and identify the relative strengths of the two parts of the amplitude in the data.

In summary, we have analyzed the possible manifestation of the f_1 trajectory in J/ψ elastic photo-production at high energy and large momentum transfers. The trajectory parameters are taken from the prediction of Ref. [11] and strength $g_{V f_1 \gamma}$ is estimated using [12]. It is found that the f_1 exchange contribution can significantly influence the differential cross section at large $|t|$. We have presented predictions showing the f_1 effect on several spin observables. In particular, we have shown notable effects in single beam and double beam-target and parity asymmetries. It should be noted that our prediction is based on the assumption of the zero slope of the f_1 trajectory discussed in Ref. [11], in which two physical grounds for almost zero slope of the f_1 trajectory were given as (i) there is a nonvanishing

contribution to the elastic pp scattering at high energy due to such f_1 trajectory and (ii) f_1 -meson exchange is deeply related to the axial anomaly which is associated with the instanton fluctuations whose space scale is much smaller than the scale of confinement. On the contrary, if the slope of f_1 trajectory is finite, we expect strong decreasing of its contribution both in s -dependence of the $\sigma_{tot}, d\sigma/dt(t=0)$ and in t -dependence of $d\sigma/dt(t=0)$ at large s and in consequence, any deviation from the standard Pomeron model for all the polarization observables discussed in our paper would disappear. Experimental test of our predictions will be a useful step towards understanding the structure of the vector meson photoproduction amplitude at large $|t|$. To test the effect of the f_1 trajectory contribution alone, it might be advantageous to use the other light vector meson (ρ, ϕ) photoproductions discussed in Ref. [11]. However, if non-trivial interference effects in spin variables predicted in this work could be observed in experiment, it will not only be just a supplementary support for the f_1 trajectory but also a good test of the hard Pomeron contribution as well, because the hard Pomeron is important only in the J/ψ photoproductions.

We should emphasize that the present investigation is the first step from the point of view of a dynamical treatment of the problem, as, for example, has been done for effective two-gluon model of Pomeron [18]. Here, we do not know the sign of $g_{Vf_1\gamma}$ vertex, and have predicted only the absolute value of beam-target asymmetry. Moreover, it would be desired to generate the the corresponding form factor independently.

Finally, the experimental facilities like SPring-8, RHIC and HERA have plans to work more on polarized vector meson production. Our aim here is to find a clear non-trivial effect for the manifestation of the f_1 trajectory which reflects some new physics. Without the data on the experimental/accelerator resources which are needed to perform this measurement, it is rather difficult to give a detailed and complete analysis on the feasibility at present. We can say that very high luminosity, hopefully larger than $10^{32}cm^2sec^{-1}$, might be necessary to actually test our prediction since the expected cross section at large $|t|$ regions where the predicted effect becomes evident, is quite small. We hope that such high luminosity could be realized in the forthcoming experiments so that we can have some good results to support this trajectory and also to establish its manifestation in QCD.

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FIGURES

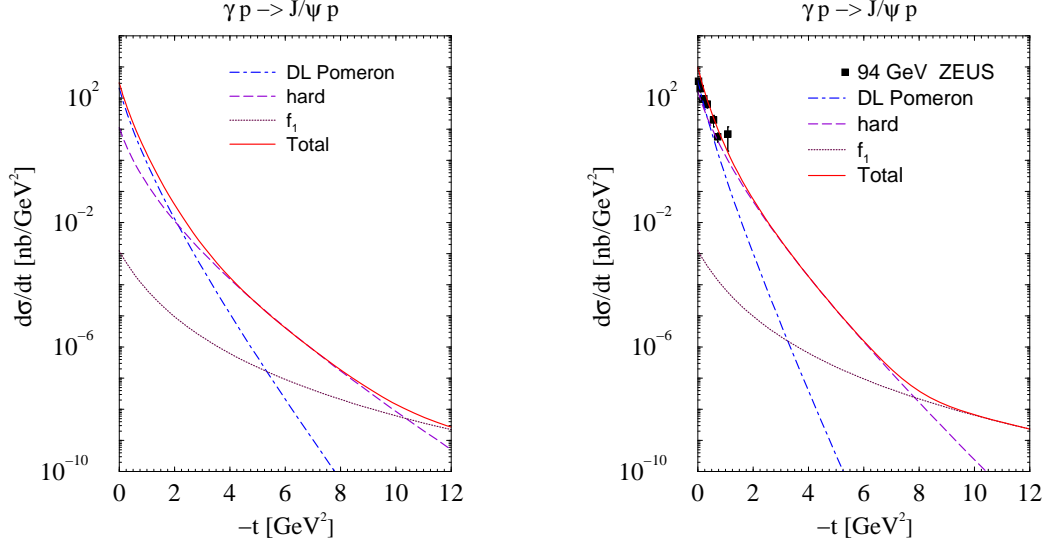


FIG. 1. The differential cross section as a function of $-t$ for $W = 20$ GeV (left panel) and 94 GeV (right panel). The dot-dashed and long-dashed lines are the soft Pomeron and hard Reggeon exchanges, the dotted line is the f_1 trajectory and the solid line represents the sum of all channels. The data points at the right panel for $W = 94$ GeV are taken from [19].

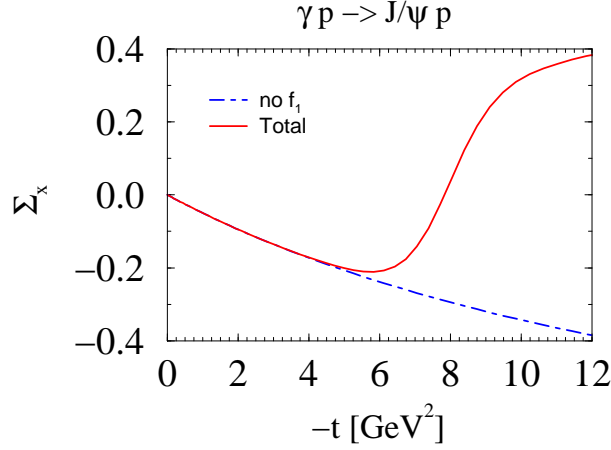


FIG. 2. The beam asymmetry Σ_x as function of $-t$ at $W = 94$ GeV. The solid and dot-dashed lines are calculation with and without f_1 trajectory, respectively.

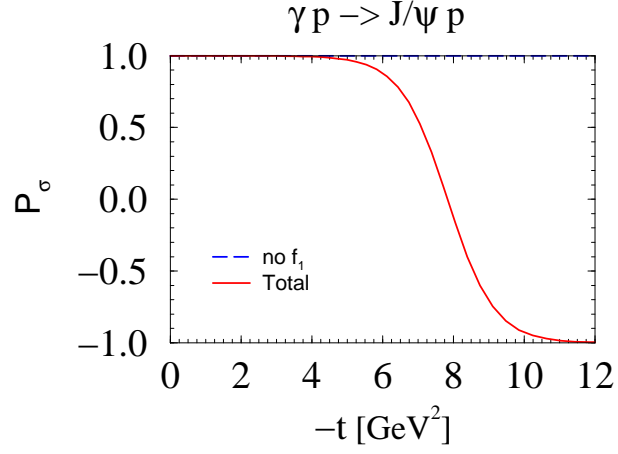


FIG. 3. The parity asymmetry as function of $-t$. Notation is the same as in Fig. 2.

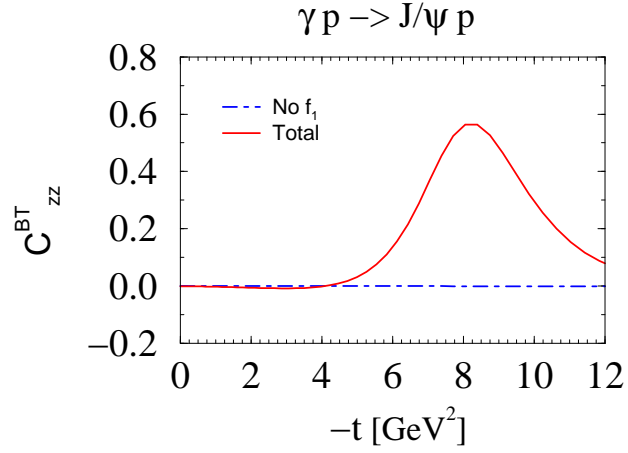


FIG. 4. The beam target asymmetry as function on $-t$. Notation is the same as in Fig. 2.